The Influence of Paste Content, Water-to-Solid Ratio and Binder Blend on Compressive Strength and Workability of Ambient Temperature Cured Alkali Activated Concrete

Rafeet, A. M., Vinai, R., Sha, W., & Soutsos, M. (2017). The Influence of Paste Content, Water-to-Solid Ratio and Binder Blend on Compressive Strength and Workability of Ambient Temperature Cured Alkali Activated Concrete. In *Proceedings of the 1st International Conference on Cement and Concrete Technology: International Cement and Concrete Technology Conference- 20-22 Nov 2017, Oman* (pp. 298-306). The Institute of Concrete Technology.

Published in:
Proceedings of the 1st International Conference on Cement and Concrete Technology

Document Version:
Publisher's PDF, also known as Version of record

The Influence of Paste Content, Water-to-Solid Ratio and Binder Blend on Compressive Strength and Workability of Ambient Temperature Cured Alkali Activated Concrete

A.M. Rafeet
Salalah College of Technology, Salalah, Sultanate of Oman

R. Vinai, W. Sha & M. N. Soutsos
Queen's University Belfast, Belfast, United Kingdom

ABSTRACT: Alkali-Activated Concretes (AACs) or Geopolymers (GP) are considered as potential candidates to play the role of binders substituting Portland cement (PC) in concrete. However, these materials differ from PC in terms of fresh properties (setting time, slump), mechanical properties (strength development, elastic features), and mix proportions. Better understanding of these engineering properties can help to design low CO_2 footprint AAC formulations for different construction applications. AACs despite demonstrating promising strength and workability potentials, are still not widely used at an industrial scale, mainly due to the lack of a widely accepted standardised mix design method that fulfils the design requirements such as strength, workability and setting time. In this paper, the proportioning of ambient temperature cured AAC produced from pulverised fuel ash (PFA) and ground granulated blast furnace slag (GGBS) activated with a mixture of sodium hydroxide and sodium silicate solution is discussed. The influence of paste content, water to solid ratio (W/S) and binder blend (PFA/GGBS) ratio was studied. It was found that the strength increased with the increase of GGBS content in the blend. The paste content was found to greatly affect the workability of AAC whereas its influence on strength was insignificant in the investigated range. The influence of W/S ratio on strength was found to be insignificant until a certain ratio beyond which a noticeable drop was detected.

1 INTRODUCTION

Concrete properties such as strength development, setting time, workability, durability and shrinkage are significantly influenced by mix parameters such as W/S ratio, dosage and type of activators, aggregate volume, etc. Thus, in order to enhance the chances of the industrial uptake of AAC, sufficient experimental data banks are essential for establishing mix design procedures for AAC which meet the required performances at lower environmental impact and lowest possible cost.

In order to develop mix design procedures for AAC to suit different applications more insight is required on both the fresh and hardened properties of this promising technology. Over the past decade researchers have started exploring the properties of AAC and comparing them with those of PCC. The majority of these studies were focused on PFA also known as fly ash based AAC (Sofi et al. 2007; Wongpa et al. 2010; Olivia and Nikraz 2011; Joseph and Mathew 2012; Sayyad and Patankar 2013; Hardjito et al. 2004; Hardjito and Rangan 2005; Rangan et al. 2006; Wallah and Rangan 2006; Junaid et al. 2015). These investigations helped to provide fundamental knowledge on the parameters influencing the properties of fly ash based geopolymer concrete. There is a common understanding among researchers that factors such as type and dosage of activators, water-to-solid ratio (W/S), elevated temperatures curing (in the range of 60 to 100°C) and curing duration are the main factors controlling the properties of fly ash based concrete. Studies reported that reinforced structural elements such as full scale beams and columns showed elastic and strength properties similar to those of PCC (Rangan et al. 2006; Yost et al. 2013). Fly ash based geopolymer concrete mainly requires both high chemical dosages and elevated temperature curing to achieve satisfactory mechanical properties. This may lead to practical limitations as a result for the requirement for elevated temperature treatment, and higher risks due to handling high concentration alkaline solutions. It also increases the CO_2 footprint of AAC (McLellan et al. 2011 and Witherspoon et al. 2009). To overcome these hurdles, GGBS is used as a sole binder or blended with PFA to produce concrete cured at ambient temperature with good mechanical properties and relatively lower requirement for activator dosages. However, this option also imposed some practical challenges such as quick setting of high calcium AAC systems. The setting problem has been highlighted in the literature without pointing out conclusive solutions to tackle the issue. Chemical admixtures used for PC appear either ineffective or detrimental when used in AAC (Provis and Deventer 2014). It was recently reported that increasing the W/S ratio in blended PFA/GGBS can increase the initial setting time of AAC (Vinai et al. 2016). Thus more work is required on both the fresh and hardened properties taking into account the technological features of AAC.

Few studies can be found on blending PFA/GGBS to produce AAC (Lee and Lee 2013; Deb et al. 2014; Xin et al. 2014; Ismail 2013). The main conclusions from these studies were that the compressive strength increased with the increase in the slag content whereas a drop in concrete slump was reported. In most of these studies a fixed binder content of around 400 kg/m^3 was adopted, and there was no control over the workability. Furthermore, the content of GGBS used was limited to lower than 30% of the total binder content due to setting related issues. Aiken et al. (2017) reported that blended PFA/GGBS mixes were more durable than Portland cement concrete mixes in the resistance of silage effluent.

Optimizing AAC mixes with minimum binder content, minimum or no heat treatment requirement and minimal chemical dosages can lead to sustainable concrete products with low embodied energy, low cost and safe handling of chemicals (Ken et al. 2015; Provis et al. 2015). Therefore, in this study the influence of binder blend, paste content and W/S ratio on compressive strength and workability of different PFA/GGBS AAC blends was investigated.

2 MATERIALS AND EXPERIMENTAL METHODS

2.1 *Binders*

The binders used in this study were Pulverized Fuel Ash (PFA) and Ground Granulated Blast Furnace Slag (GGBS). PFA was supplied by Power Minerals Ltd. – former Hargreaves Company, Drax Power Station, North Yorkshire. GGBS was dispatched by Civil and Marine Ltd – Hanson Company and member of the Heidelberg Cement Group, West Thurrock, Essex, UK. The chemical compositions obtained by X-ray fluorescence (XRF) are shown in Table 1.

Table 1: XRF elemental oxides for the binders

XRF Elemental Oxide	PFA Mass-%	GGBS Mass-%
CaO	2.2	43.7
SiO_2	46.8	29.4
Al_2O_3	22.5	11.2
Fe_2O_3	9.2	0.4
Na_2O	0.9	1.0
K_2O	4.1	0.9
SO_3	0.9	1.8
MgO	1.3	6.9
TiO_2	1.1	0.7
Loss on Ignition (LOI)	3.6	2.4

2.2 *Activators*

The activators used in this study were commercial grade (99% purity) sodium hydroxide (NaOH), and sodium silicate solution with SiO_2:Na_2O ratio = 2:1 (Na_2O 12.8%, SiO_2 25.5%, water 61.7%), supplied by Fisher Scientific UK. NaOH solution with the required concentration was prepared by dissolving NaOH prills in tap water and the solution was then left to cool off for at least 24 hours before use. Sodium hydroxide solution was used to adjust the activating solution in order to achieve the required Alkali Dosage (M+) which is calculated as the mass ratio of Na_2O in the activation solution to the total binder content (Na_2O/binder) and Alkali Modulus (AM) which is defined as the mass ratio of Na_2O to SiO_2 in the activation solution (Na_2O/SiO_2).

The water/solids ratio (W/S) is defined as the ratio between total mass of water (i.e. tap water + water in the alkali solutions) and the total solid mass (i.e. mass of binder + mass of alkali solids). Lower W/S ratios were found to cause rapid setting of AAC mixes and a minimum W/S ratio was suggested in a previous study to design AAC mixes with initial setting times deemed acceptable for concrete applications (Vinai et al. 2016).

Binder content is defined as the mass of solid precursors (PFA+GGBS) per cubic metre of concrete. Paste volume is defined as the volume of the solid precursor + activating solutions + added water, per cubic metre of concrete. Paste content is defined as the percentage of paste volume over the total concrete volume.

2.3 *Aggregate*

Crushed basalt of two sizes (4/10 mm and 10/20 mm) and lake sand (0/4 mm) were used as aggregate in the following proportions (in volume): 40% sand over total aggregate, ratio between coarse aggregate sizes equal to 40%/60% for 4/10 mm and 10/20 mm. The particle size distribution of the aggregate mix is shown in Figure 1. Aggregates were first oven-dried at 105 °C overnight for avoiding the inclusion of unknown water mass in the system. Subsequently, they were wetted with a mass of water calculated according to their 1-hour absorption rate (see Table 2). The aim of this process was to avoid aggregate to absorb water that should be available for the lubrication and for the chemical reaction of the system. The water used for the saturation of the aggregate was not considered in the overall W/S ratio.

100-mm cube concrete samples were cast for compressive strength measurement. Samples were cured in plastic boxes with minimum relative humidity of 90 % and were kept at constant temperature of 20 °C throughout the curing period. The relative humidity in plastic boxes was checked regularly through a portable digital humidity reader positioned inside the boxes. Three cubes were tested in compression at 28 days according to BS 1881-116:1983. Average strength and standard deviation were calculated.

3 RESULTS AND DISCUSSION

It was found from a previous study that paste contents above 33% resulted in very fluid concrete mixes, making the control of the workability very difficult (Vinai et al. 2016). High paste content

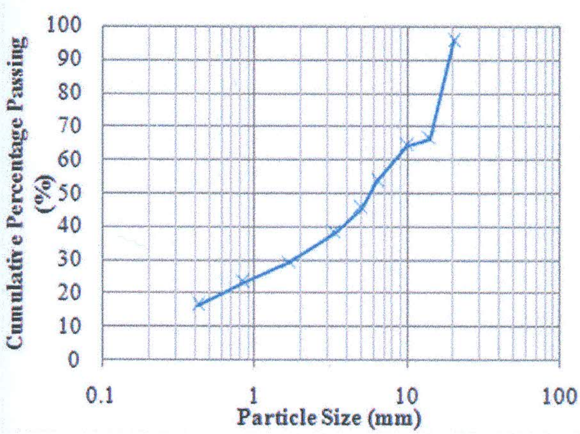

Figure 1: Particle size distribution for aggregate mix

Table 2: Physical properties of aggregate

Material	Density on an oven-dried basis (g/cm^3)	1-hour water absorption based on SSD condition (%)
Sand 0/4	2.7	0.9
Crushed basalt 4/10	2.8	1.4
Crushed basalt 10/20	2.8	1.2

Table 3: Void content of aggregate mix

Packing condition	Bulk density (kg/m^3)	Void content (%)
Loose	1797.5	34.3
Vibrated	2125.8	22.3

also caused segregation and bleeding of the AAC. Furthermore, high paste content also increased the cost and the environmental impact of AAC due to the increase in the binder content, which corresponds to an increase in the quantity of activators. Also from the bulk density and the void content of the aggregate mix measured with a 7 l container in a loose and vibrated state shown in Table 3, it can be seen that the required paste content to fill the voids can be in the range of 22-34%.

Therefore, in the current study the influence of paste content on compressive strength and workability was investigated in the range of 30-33%. The mix proportions for the concrete mixes are shown in Table 4.

The 28-day compressive strength of 80/20 blend, as can be seen from Figure 2 (A), was in the range of 35 to 40 MPa for the studied paste content range (30-33%). The influence of paste content in the range of 30-33% on compressive strength was found insignificant. Workability, on the other hand, was considerably influenced by the increase in the paste content especially when 33% paste content was adopted. As can be seen from Figure 2 (B), the slump for 30% paste content was in the range of 0-40 mm (class S1 as classified by BS 8500-1, 2015) despite the variation in W/S ratio in the range of 0.37 to 0.41. Increasing the paste content to 31% increased the slump to fall in class S2 (50-90 mm slump) which can be considered as satisfactory for a wide range of concrete applications. Further increase in the paste content (33%) caused a further increase in the slump i.e. in the range of 100-200 mm) with a more noticeable effect of W/S ratio in the investigated range (0.37 to 0.41).

The compressive strength increased with the increase in the GGBS content from 20 to 40%. In 60/40 AAC mix, the highest compressive strength obtained was around 60 MPa and increasing the paste content appeared not to influence the compressive strength as shown in Figure 2 (C). Low W/S ratios i.e. lower than 0.38 along with 30% paste content resulted in very stiff mixes for which the strength could not be measured.

W/S ratios in the range of 0.36 to 0.41 had negligible effect on the 28-day compressive strength of 60/40 AAC mix (see Figure 2 (C)). This can be attributed to the role of water in the reaction mechanism. It takes part in the hydration and strength development of high calcium content alkali activated binders. However, the slump was significantly affected by increasing the paste content from 30 to 33%. Slump values in the range of 50 to 220 mm were obtained as shown in Figure 2 (D).

30/70 blend or the AAC mix with the highest GGBS content required higher W/S ratios (above 0.42) compared to the mixes discussed above. This was to avoid rapid setting of high GGBS mixes as discussed in Vinai et al. (2016). The highest compressive strength for this blend was in the range of 70 to 80 MPa with smaller influence of the water content up to a W/S ratio of 0.46, (see Figure 2 (E)). After that value, a slight drop in strength was observed. The workability

Table 4: Mix proportions for different PFA/GGBS blends in kg (for the production of 1 m^3 of concrete)

Mix Code	PFA	GGBS	Sodium hydroxide	Sodium silicate	Water	Sand 0/4 mm	Aggregate 4/10 mm	Aggregate 10/20 mm	W/S ratio	Paste proportion %
80M1	281	70	68	83	50	753	470	691	0.37	30
80M2	274	69	66	81	56	753	470	691	0.39	30
80M3	267	67	64	79	62	753	470	691	0.41	30
80M4	291	73	70	86	51	742	464	681	0.37	31
80M5	283	71	68	83	58	742	464	681	0.39	31
80M6	276	69	67	81	64	742	464	681	0.41	31
80M7	309	77	75	91	55	721	450	661	0.37	33
80M8	301	75	73	89	62	721	450	661	0.39	33
80M9	294	73	71	86	69	721	450	661	0.41	33
60M1	209	139	67	82	57	753	470	691	0.39	30
60M2	203	136	66	80	63	753	470	691	0.41	30
60M3	198	132	64	78	69	753	470	691	0.43	30
60M4	219	146	70	86	56	742	464	681	0.38	31
60M5	216	144	69	85	59	742	464	681	0.39	31
60M6	213	142	69	84	62	742	464	681	0.4	31
60M7	239	159	77	94	52	721	450	661	0.36	33
60M8	230	153	74	90	63	721	450	661	0.39	33
60M9	219	146	70	86	76	721	450	661	0.43	33
30M1	103	240	66	81	68	753	470	691	0.42	30
30M2	98	228	63	77	79	753	470	691	0.46	30
30M3	95	223	61	75	85	753	470	691	0.48	30
30M4	106	248	68	83	70	742	464	681	0.42	31
30M5	101	236	65	79	82	742	464	681	0.46	31
30M6	99	230	64	77	88	742	464	681	0.48	31
30M7	113	264	73	89	75	721	450	661	0.42	33
30M8	108	251	69	84	87	721	450	661	0.46	33
30M9	105	245	68	82	93	721	450	661	0.48	33

of the 30/70 blend was found to be in a narrow range especially at lower paste content, i.e. 30%, where the slump fell in class S2 (50-90 mm) for all the investigated W/S ratios, as can be seen from Figure 2 (F). Increasing the paste content to 31% led to a wider spread of the slump classes (S2 to S4); the slump continued to increase with further increase in the paste content. Slump values of 100 to 220 mm were achieved with paste content of 33% (Figure 2 (F)). Wider spectrum of slump classes (S2 to S5) can be achieved with adjusting both the paste content (30 to 33%) and W/S ratio (0.42 to 0.46). This allows more flexibility in mix proportioning to avoid rapid setting, and satisfy the strength and workability requirements.

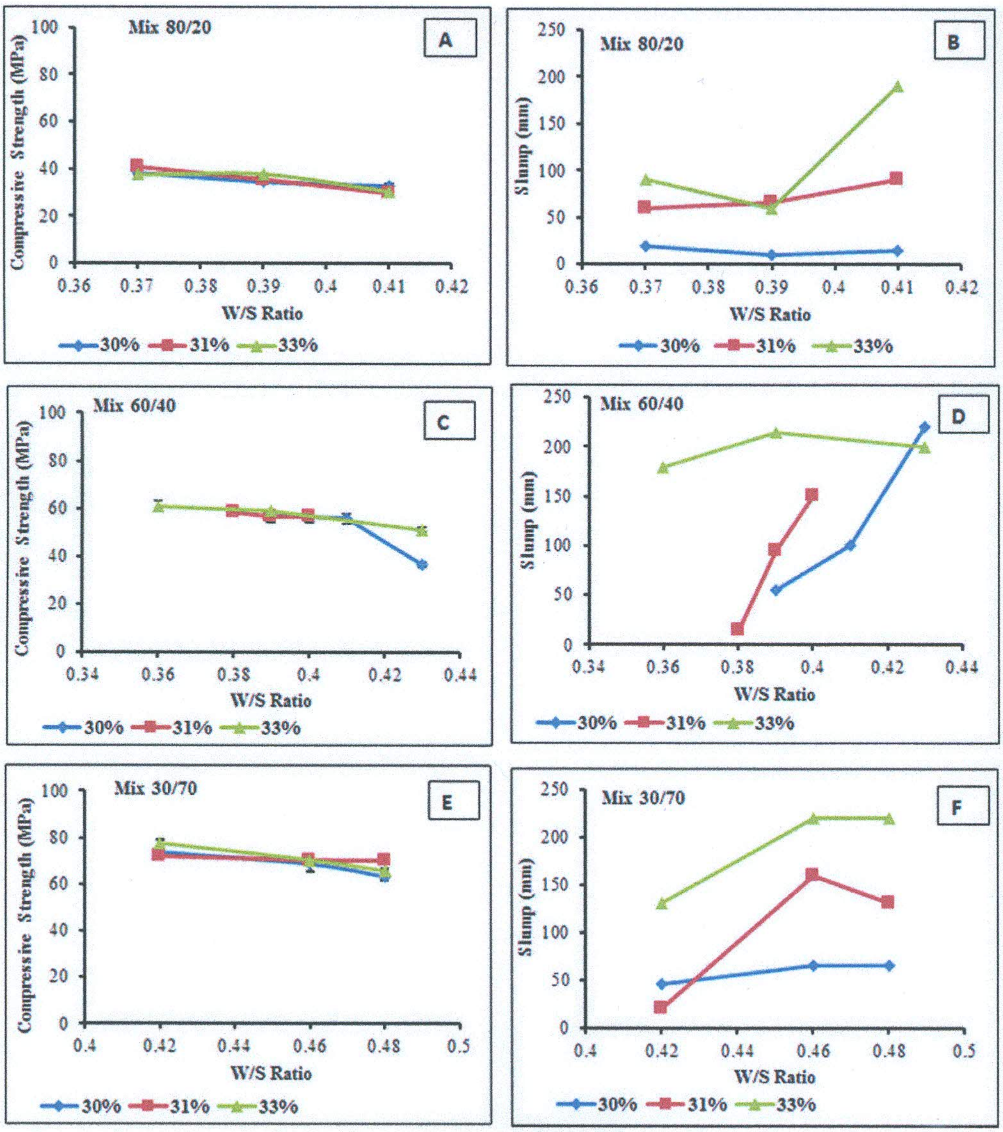

Figure 2: 28-day compressive strength and slump of the different PFA/GGBS mixes

4 CONCLUSIONS

- In this study the effect of parameters such as GGBS content, W/S ratio and paste content on compressive strength and workability of AAC is investigated. The following conclusions can be drawn:
- The compressive strength increased with the increase in the GGBS content in the blend. The compressive stength was doubled when the GGBS content was increased from 20 to 70%.
- The effect of W/S ratio on the compressive strength reduced with the increase in GGBS content.
- Paste contents in the range of 30-33% showed no significant effect on the compressive strength of AAC in the studied blends. However, the slump of AAC was found to be significantly affected by varying this parameter.
- Binder contents in the range of 320 to 380 kg/m^3 can be recommended for AAC mixes with compessive strengths ranging from 30 to 80 MPa, and a wide range of slump.

ACKNOWLEDGEMENTS

This research was carried out in the framework of the SUS-CON "Sustainable, Innovative and Energy-Efficient Concrete, based on the Integration of All Waste Materials" project, which has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under Grant Agreement No. 285463 (Call FP7-2011-NMP ENV-ENERGY-ICT-EeB).

REFERENCES

Aiken, T. A., Sha, W., Kwasny, J. and Soutsos, M.N., (2017). Resistance of geopolymer and Portland cement based systems to silage effluent attack. Cement and Concrete Research, 92, pp.56-65.

BSI, 1983. Testing concrete. Part 116: method for determination of compressive strength of concrete cubes. BSI 1881-116.

BSI, 2015. BS 8500-1; Concrete- Complementary British Standard to BS EN 206-1; Part 1:Method of specifying and guidance for the specifier.

Deb, P. S., Nath, P. and Sarker, P. K., (2014). The effects of ground granulated blast-furnace slag blending with fly ash and activator content on the workability and strength properties of geopolymer concrete cured at ambient temperature. Materials and Design, 62, pp.32-39.

Hardjito, D. and Rangan, B., (2005). Development and properties of low-calcium fly ash-based geopolymer concrete. Research Report GC 1. Peth, Australia, Curtin University of Technology, Faculty of Engineering.

Hardjito, D., Wallah, S. E., Sumajouw, D. M., and Rangan, B. V., (2004). Factors influencing the compressive strength of fly ash-based geopolymer concrete. Civil Engineering Dimension, 6(2), pp.88-93.

Hung, C. and Chang, J., (2013). The influence of mixture variables for the alkali-activated slag concrete on the properties of concrete. Journal of Marine Science and Technology, 21(3), pp.229-237.

Ismail, I., (2013). Durability as a function of microstructure of alkali-activated slag/fly ash binders. (Doctoral dissertation, University of Melbourne, Australia).

Joseph, B. and Mathew, G., (2012). Influence of aggregate content on the behavior of fly ash based geopolymer concrete. Scientia Iranica, 19(5), pp.1188-1194.

Junaid, M. T., Kayali, O., Khennane, A. and Black, J, (2015). A mix design procedure for low calcium alkali activated fly ash-based concretes. Construction and Building Materials, 79, pp.301-310.

Ken, P. W., Ramli, M. and Ban, C. C., (2015). An overview on the influence of various factors on the properties of geopolymer concrete derived from industrial by-products. Construction and Building Materials, 77, 370-395.

Lee, N. K. and Lee, H. K., (2013). Setting and mechanical properties of alkali-activated fly ash/slag concrete manufactured at room temperature. Construction and Building Materials, 47, pp.1201-1209.

McLellan, B. C., Williams, R. P., Lay, J., Van Riessen, A. and Corder, G. D., (2011). Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement. Journal of Cleaner Production, 19(9), pp.1080-1090.

Olivia, M. and Nikraz, H. R., (2011). Strength and water penetrability of fly ash geopolymer concrete. Journal of Engineering and Applied Sciences, 6(7), pp.70-78.

Provis, J. L. ed., (2014). Alkali activated materials. Springer.

Provis, J. L., Palomo, A. and Shi, C., (2015). Advances in understanding alkali-activated materials. Cement and Concrete Research, 78, pp.110-125.

Rangan, B. V., Sumajouw, D., Wallah, S. and Hardjito, D., (2006). Reinforced low-calcium fly ash-based geopolymer concrete beams and columns. cipremier.com.Available at:http://cipremier.com/e107_files/downloads/Papers/100/31/100031003.pdf [Accessed March 11, 2014].

Sayyad, A. S. and Patankar, S. V., (2013). Effect of steel fibres and low calcium fly ash on mechanical and elastic properties of geopolymer concrete composites. Indian Journal of Materials Science, 2013, pp.1-8.

Sofi, M., Van Deventer, J. S. J., Mendis, P. A., and Lukey, G. C., (2007). Engineering properties of inorganic polymer concretes (IPCs). Cement and Concrete Research, 37(2), pp.251-257.

Vinai, R., Rafeet, A., Soutsos, M. and Sha, W., (2016). The role of water content and paste proportion on physico-mechanical properties of alkali activated fly ash–ggbs concrete. Journal of Sustainable Metallurgy, 2(1), pp.51-61.

Wallah, S. E. and Rangan, B. V, (2006). Low-calium fly ash-based geopolymer concrete :long-term properties, Perth, Australia.

Witherspoon, R., Wang, H., Aravinthan, T. and Omar, T.; (2009). Energy and emissions analysis of fly ash based geopolymers. SSEE 2009: Solutions for a Sustainable Planet, p.311.

Wongpa, J., Kiattikomol, K., Jaturapitakkul, C. and Chindaprasirt, P., (2010). Compressive strength, modulus of elasticity, and water permeability of inorganic polymer concrete. Materials and Design, 31(10), pp.4748-4754.

Xin, L., Jin-yu, X., Weimin, L. and Erlei, B., (2014). Effect of alkali-activator types on the dynamic compressive deformation behavior of geopolymer concrete. Materials Letters, 124, pp.310-312.

Yost, J. R., Radlińska, A., Ernst, S., Salera, M. and Martignetti, N. J., (2013). Structural behavior of alkali activated fly ash concrete. Part 2: structural testing and experimental findings. Materials and Structures, 46(3), 449-462.